Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 75 (2015) 2764 – 2771
Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Energy Technology Assessment of Shale Gas 'Fracking' – A UK Perspective

Geoffrey P. Hammond[a,b,]*, Áine O'Grady[a] and David E. Packham[a,b]

[a]Department of Mechanical Engineering,University of Bath, Bath. BA2 7AY UK
[b]Institute for Sustainable Energy and the Environment, University of Bath, Bath. BA2 7AY UK

Abstract
There is at present much interest in unconventional sources of natural gas, especially in shale gas which is obtained by hydraulic fracturing, or 'fracking'. Boreholes are drilled and then lined with steel tubes so that a mixture of water and sand with small quantities of chemicals – the fracking fluid – can be pumped into them at very high pressure. The sand grains that wedge into the cracks induced in the shale rock by a 'perforating gun' then releases gas which returns up the tubes. In the United Kingdom (UK) exploratory drilling is at an early stage, with licences being issued to drill a limited number of test boreholes around the country. But such activities are already meeting community resistance and controversy. Like all energy technologies it exhibits unwanted 'side-effects'; these simply differ in their level of severity between the various options. Shale gas may make, for example, a contribution to attaining the UK's statutory 'greenhouse gas' emissions targets, but only if appropriate and robust regulations are enforced. The benefits and disadvantages of shale gas fracking are therefore discussed in order to illustrate a 'balance sheet' approach. It is also argued that it is desirable to bring together experts from a range of disciplines in order to carry out energy technology assessments. That should draw on and interact with national and local stakeholders: 'actors' both large and small. Community engagement in a genuinely participative process – where the government is prepared to change course in response to the evidence and public opinion - will consequently be critically important for the adoption of any new energy option that might meet the needs of a low carbon future.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Shale gas; hydraulic fracturing; resources; economic and environmental impacts; induced seicity; public acceptance; regulation

1. Introduction

1.1 Background

Economic growth is underpinned by energy sources of various kinds. But all energy technologies have unwanted 'side-effects'; they simply differ in their level of severity. Hydraulic fracturing, or 'fracking', for shale gas is a particularly controversial energy option that is receiving significant development support by the present United Kingdom (UK) Coalition Government. Licences have been issued by the *Department of Energy and Climate Change* (DECC) to drill a limited number of test boreholes around the country (see, for the case of England, [1]). These boreholes are then lined with steel tubes, and a mixture of water and sand with small quantities of chemicals – the fracking fluid - is pumped into them at very high pressure. The sand grains that wedge into the cracks induced in the shale rock by a 'perforating gun' then releases gas which returns up the tubes (see Fig. 1). The UK Government is attracted by the possible benefits of securing large quantities of shale gas for the UK as an energy 'game changer': leading to a potential 'Golden Age of Gas', according to the *International Energy Agency* (IEA) [2]. The IEA sees shale gas as contributing about 14% to global gas production by 2035. However, the exploitation of fracking will involve a range of advantages and disadvantages ('credits and debits') that will fall disproportionately on different sections of British society. So it is necessary to

* Corresponding author. Tel.: +44 1225 386168; fax: +44 1225 386928.
E-mail address: G.P.Hammond@bath.ac.uk

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.526

identify the components of a shale gas fracking ‘balance sheet’ of the sort employed in technology assessment [3-5] to evaluate its impact on communities, countryside and wildlife and whether it is compatible with Britain's move towards a low carbon future in 2050 and beyond.

1.2 Historical Development of Fracking for Shale Gas

The technique of hydraulic fracturing began in the United States of America [6] in around 1949 when the first two, small-scale commercial vertical wells were initiated in Oklahoma and Texas respectively [7,8]. But it was not until 1997 that the process known as ‘slickwater fracturing’ was developed and implemented in the Barnett Shale by the then Mitchell Energy . This is a method that involves adding chemicals to water to increase the flowrate at which the fracking fluid can be pumped down a well-bore to fracture extremely dense shale. The fracking fluid is made up of around 98.50% water, 1.00% sand, and 0.05-0.50% chemical additives [6]. These chemicals are friction reducers, usually a polyacrylamide, together with biocides, surfactants and scale inhibitors. Biocides prevent organisms from blocking the ‘up downhole’ and fissures, whereas surfactants keep the sand grains in fluid suspension. Other chemicals that are sometimes employed include benzene, chromium, and a number of other compounds [6]. North American fracking companies keep the composition of this chemical ‘cocktail’ secret , claiming commercially confidentiality, although an independent study identified about 650 separate chemicals compounds However in the UK, companies are obliged under the *Water Resources Act* 1991 to disclose the composition used. Many of these are known to be toxic and widespread concern has been expressed over potential water contamination [6, 9-11]. Nevertheless, it was this pressure-induced slickwater fracturing (see again Fig. 1) that made shale gas extraction economical by radically reducing the costs of horizontal fracking [6].

1.3 The Issues Considered

The possible benefits and disbenefits of shale gas fracking include economic, environmental, safety and social consequences [12] for the UK. Here they are discussed as an example of a ‘balance sheet’ approach: analysis rather than advocacy. In order to draw up an objective and rigorous set of credits and debits for shale gas fracking (or indeed other critical technologies) as part of a national dialogue, it is argued that is desirable to bring together experts from a wide range of disciplines to undertake *energy technology assessments* (ETA) [5] that exhibit balance, objectivity and broad public participation. This should draw on and interact with national and local stakeholders: ‘actors’ both large and small. Community engagement will consequently be critically important for the adoption of any new energy option that might meet the needs of a low carbon future. This contribution is part of an ongoing research effort aimed at evaluating and optimising the performance of various sustainable energy systems (see, for example, Hammond *et al.* [13] and Hammond and Hazeldine [14]) in the context of transition pathways [15,16] to the statutory target of a reduction of UK emissions by at least 80% from 1990 levels by 2050 . It is aimed at illustrating the consequences of shale gas fracking within a UK setting in the light of imperfect, and sometimes contradictory, information. Nevertheless, such assessments provide a valuable evidence base for communities, developers, policy makers, and other stakeholders.

2. The Potential Shale Gas Resource in the UK

On the positive side of the ‘balance equation’ is the prospect that fracking could potentially yield significant quantities of shale gas to meet the Britain’s energy needs. In contrast (on the negative side), the IEA warn that the significant global development of this gas would put the world on a trajectory towards a long-term temperature rise of over 3.5°C; well above the widely suggested 'safe' level of 2°C [2]. The *British Geological Survey* (BGS) [17] has estimated the possible reserves of shale gas in the *Bowland-Hodder* study area or ‘play’ (encompassing national parks and major cities) and the Weald in the South East for DECC, see Fig. 2. The great uncertainties inherent in such provisional estimates can only be refined by extensive investigative drilling, possibly requiring hundreds wells [18,19]. However, making assumptions about recovery rates (based on experience at over 10,000 US fracking sites) and the proportion of available resources extractable in the UK, the BGS suggest [17] that recoverable shale gas resources might be equivalent to some 25-50 years of current UK natural gas (NG) demand. That would significantly contribute to Britain’s energy security and independence.

3. Shale Gas Socio-Economic and Market Issues

The UK balance of payments would obviously benefit significantly from the large-scale development of shale gas extraction, although it is unlikely that gas bills for household and industrial consumers would fall dramatically as they have done in North America. This is because the USA is effectively a “natural gas island” with very limited ‘Liquefied Natural Gas’ (LNG) imports via the gas trading hubs of Europe [20]. In the USA, supplies of conventional NG have been drying up, and unconventional gas (including from shales) has been able to grow rapidly to meet some 60% of marketed production, according to the IEA [2]. Many US energy analysts believe that this fall in gas prices to historically low levels has been caused by advances in extraction techniques, particularly fracking, driving down production costs. Much of this shale gas production occurred as an almost ‘free’ co-product of unconventional oil extraction. In contrast, the UK is part of the wider European natural gas market [21] where the gas price is determined by the supply and demand for indigenous natural gas, imports from Russia, and LNG from North Africa and Middle East. Shale gas supplies in the UK will only provide a small fraction of those in this wider gas market. So the household economic benefits in Britain are therefore unlikely to live up to the hopes of the UK Prime Minister (David Cameron), who argued in the *Daily Telegraph* newspaper (11/08/13) that it would "see lower energy prices in this country". David Cameron also cited job creation as another socio-economic benefit. That will undoubtedly follow successful shale gas exploitation, but it is unclear whether this would be any greater than for equivalent programmes aimed at supporting the adoption of energy demand reduction measures or small-scale low carbon energy options.

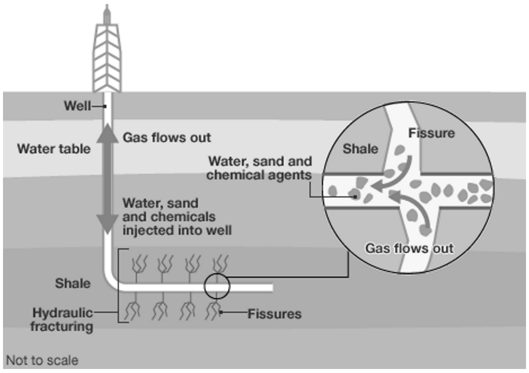


Fig. 1. The shale gas 'fracking' process (*Source:* adapted from *Transition Haslemere*.)

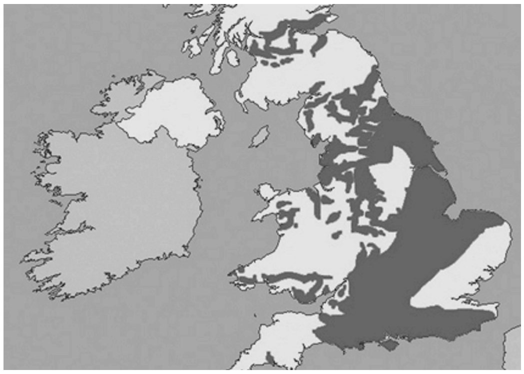


Fig. 2. Potential UK shale gas reserves [sites - dark shading] (*Source:* adapted from *Standpoint* magazine, April 2012; after BGS [17].)

Perhaps the most important socio-economic issue concerns the distribution of the benefits and costs of shale gas fracking between various communities and demographic groups. Depending on how much shale gas can be exploited, the UK overall could benefit from improved energy security and reduced balance of payments, but it is local communities that will bear the risks of fracking. The Coalition Government intends to offset this potential harm by encouraging (but not requiring) the extraction industry to sign up to a charter that will guarantee payments of some £100,000 to communities located near shale gas exploratory wells. If the gas is ultimately exploited, then they would receive one per cent of the resulting revenues.

4. Induced Seismicity

Great public concern over shale gas fracking was triggered in 2011 by two seismic tremors, or minor earthquakes, caused by exploratory drilling at the *Cuadrilla Resources* site at Preese Hall near Blackpool. Subsequent studies by DECC [22], aided by independent experts, together with a review of the scientific and engineering evidence on shale gas extraction undertaken by the *Royal Society* (RS) and the *Royal Academy of Engineering* [23],found that suitable controls were available to mitigate the risks of undesirable seismic activity. It was argued that the most likely cause of the Preese Hall tremors was 'induced seismicity'; caused by the injection of fracking fluid into and along faults that had already been under stress. The fault then shifts, leading to perceived surface tremors. The DECC subsequently announced the introduction of a set of requirements for new controls, permissions and risk assessments on fracking operations in 2012, including oversight by the *Health and Safety Executive* (HSE), at Preese Hall and all future shale gas exploration wells. They included a 'traffic light' seismic monitoring system [22], as advocated in the RS/RAEng study [23]. Nevertheless, earth scientists (see, for example, Davies *et al.* [24]) viewed the fault diagnosis as incomplete, and proposed the additional use of borehole imaging before injection. Recently Westaway and Younger [25] suggested that the existing regulatory limits applicable to quarry blasting could be readily applied to cover such induced seismicity. They argued that future fracking activities in the UK is only likely to cause "minor damage", and that seismic monitoring could be used to 'police' compliance with the regulatory framework.

5. Water Use and Contamination

Fracking for shale gas typically takes place several hundreds of metres below drinking water aquifers. Unconventional gas enthusiasts argue that there have been no cases of groundwater contamination due to fracking in the United States, although the US Environment Protection Agency is less confident of that and its studies are therefore continuing. Hydraulic fracturing requires large quantities of water dependent on the properties of the shale rock involved. It ranges from 10,000-30,000 m3 of water per fracking operation or well [26]. Excessive water use may lead to a fall in the availability of public water supply, ecosystem degradation and adverse effects on aquatic habitats, erosion, and changes in water temperature [26]. Abstracting water from resources under stress should therefore be avoided. Some of this water may be recyclable, although it could be contaminated, for example, by Naturally Occurring Radioactive Material (NORM). The RS/RAEng report [23] suggests that the latter are found in shales at significantly lower levels than safe exposure limits. Nevertheless, wastewaters require careful management and monitoring in order to ensure that NORMs do not become concentrated. Recycled fracking fluid could be used for ongoing fracking operations [26], except that a proportion of this is not recovered. In the USA some concern has been expressed over the possibility of methane levels in water that might be high enough to be flammable [27]. It has been asserted by DECC [27] that these are normally caused by failures in the well construction or natural background levels of methane rather than fracking per see. Indeed the RS/RAEng review [23] considered the possibility of direct groundwater contamination to be very unlikely, although it could result from faulty wells. The RS/RAEng review also warned that environmental contamination including 'faulty wells, and leaks and spills associated with surface operations' were to be expected as they are common to all oil and gas wells and extractive activities.

6. Environmental Impacts

6.1 Local Environmental Pollution, Health and Related Impacts

There are various local environmental impacts from shale gas fracking: the excessive water use, groundwater contamination and wastewater handling as discussed above, as well as noise, odours, and the disposal of solid wastes. In order to prevent contamination, the integrity of fracking wells must be ensured. Guidelines for achieving this were recommended in the RS/RAEng report [23], which are largely reflected in documents produced by the *American Petroleum Institute* and the HSE that are recommended by DECC [28]. Both well design and construction are overseen by an Independent Well Examiner and the HSE Wells Inspector. It is believed that properly designed wells should not pose a risk of contamination to underground aquifers [28]. Of course regulation, however good, is ineffective without rigorous enforcement backed by seriously deterrent penalties. In addition, there are aesthetic concerns: visual intrusion of the sort that also results from onshore wind turbine developments. Shale gas fracking requires site operations at the wellhead, as well as the collection and distribution of unconventional gas from the site [29]. Public resistance often focuses on the increased traffic and vehicle exhaust emissions, particularly those emanating from heavy road transport vehicles. Drilling often takes place on landscapes of natural beauty that include sensitive wildlife habitats [29]. Operational environmental permits for shale gas fracking in the UK are issued by the EA, NRW, or the SEPA (as appropriate) on a site-by-site basis in line with the requirements imposed in water abstraction licenses, and actual usage monitored over time.

6.2 Climate Change and Fugitive Emissions

The 2008 UK *Climate Change Act* [16] set a legally binding target of reducing the nation's greenhouse gas emissions overall by 80% by 2050 in comparison to a 1990 baseline. Gas-fired power stations emit far fewer 'greenhouse gases' (GHGs) per unit of electricity output than coal-fired ones and, for this reason, it is favoured by Helm [29] as a transitional energy option. Two of the main sources of global warming impact arising from shale gas development are the fugitive methane emissions leaked and vented during extraction processes, and carbon dioxide (CO_2) emissions from the combustion of the shale gas to produce electricity. Similarly to conventional gas, the majority of the impact is a result of the combustion of the shale gas. However, there is greater variation in fugitive methane emissions from the extraction process, depending on the given location, particularly in terms of enforced environmental legislation. Therefore, much of the controversy over the global warming impact of shale gas technology focuses on such fugitive methane. Methane is a much more powerful GHG than CO_2, although its resides in the atmosphere for only 12 years [30]. Some of it may be flared (converting it to CO_2), rather than vented, but this is not or cannot always be done.

The most recent values of global warming potential (GWP) for GHGs are provided by the *Intergovernmental Panel on Climate Change* (IPCC) [31] over three separate time horizons: 20, 100 and 500 year respectively. Scientifically speaking, the use of the three different time horizons are all equally valid for assessing GHGs. Short-lived, more potent GHG such as methane have much higher GWP over the 20 year horizon, trapping 86 times more heat than carbon over this period, compared to 34 over a 100 year horizon [31]. Some have argued that it might be more pertinent to consider methane emissions over the 20 year horizon to assess the danger it poses to our climate system in the short-term. However, the 100 year horizon has been widely used by many, providing a balance between short-term and long-term impact of GHGs on climate change. Furthermore, this is particularly appropriate given that CO_2 accumulates over time in the atmosphere, whereas methane dissipates. Accordingly, the results presented in this assessment of the lifecycle GHG emissions from shale gas are over a 100 year time horizon.

Upstream GHG emissions estimated by several studies have been collated [32-38] in order to explore the potential 'carbon footprint' of UK shale gas (see Fig. 3). The controversial study by Howarth *et al.* [38] was excluded when averaging this data, because of its relatively high estimates for fugitive emissions. Should rigorous and effective environmental legislation be introduced in the UK, this level of emissions is unlikely to be permitted. Emissions data from the *Ecoinvent* database version 2.2 [39] were used to account for UK NG when generating the latter mix; for both domestic and imported UK fuel routes [from Norway, the Netherlands, the rest of the European Union (EU), and via LNG]. The full life-cycle GHG emissions of shale gas electricity generation are compared to the NG generation using the current UK gas mix, LNG and Russian gas respectively in Fig. 4. The LNG emissions data were taken from a review undertaken previously by two of the present authors [40]. The operational (or 'stack') emissions are based on current UK technology, but may fall over time as more efficient plants come online. Total life-cycle emissions of shale gas generation were estimated to be in the range of 480-546 $gCO_2e/kWhe$, 4-18% greater than emissions from the current UK gas mix, with a central estimate of 14% greater GHG emissions. Thus, providing effective regulation to curtail fugitive emissions are in place, electricity generation using shale gas could offer significant savings in carbon emissions when displacing coal-fired generation as part of a transitional energy strategy. This result is in keeping with other estimates found in literature [32,35] and a study carried out by DECC [41], which saw a moderate disparity between conventional and unconventional gas. There are large uncertainties associated with these findings, and they should only be considered as 'indicative' until real operational data are available.

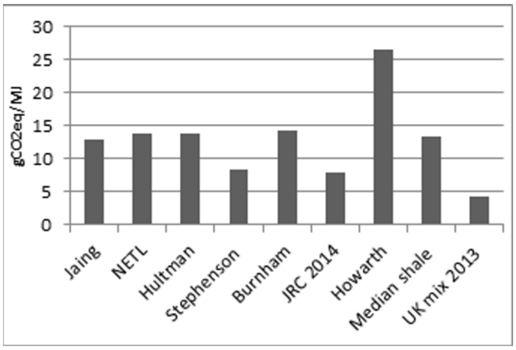


Figure 1. Central estimates for upstream GHG emissions associated with unconventional gas compared to current UK gas mix

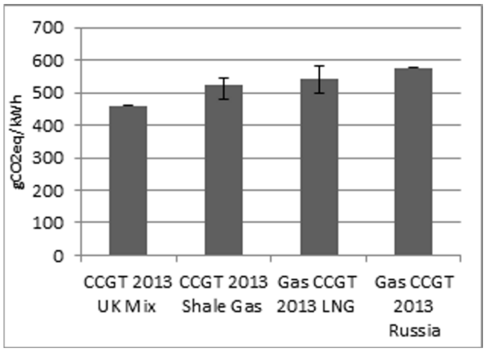


Figure 2. Life-cycle GHG emissions for gas generation with different gas sources

Sensitivity analysis performed in connection with shale gas studies have shown large ranges in the impact of shale gas, particularly in terms of fugitive emissions and the estimated ultimate recovery per well [42-44]. Hence, without effective regulation (backed by rigorous enforcement and seriously deterrent penalties) to minimise these fugitive methane emission, many hypothetical advantages of shale gas may not be realised. Legislation to address fugitive methane from shale gas have not yet been specified in the UK, however, it is envisioned that they will be treated in the same manner as fugitive methane from current UK oil and gas production. Consent for venting or flaring in this sector (reserved mainly for maintenance and emergency procedures) must be granted by DECC [45] who are committed to keeping these emissions to a technical and economic minimum.

6.3 Comparing Environmental Burdens from Different Life-cycle Impact Categories

A recent life-cycle study by Stamford and Azapagic [42] has generated some controversy in the way their results have been represented in the media: as "fracking trumps renewables". This is because the authors examined a variety of life-cycle impact categories in addition to climate change (for which their central estimate was 462 $gCO_2e/kWhe$). Shale gas was comparable or superior to conventional gas, nuclear power and renewables in terms of the depletion of abiotic resources and eutrophication, as well as freshwater, marine and human toxicities. In contrast, they found shale gas to be more environmentally damaging when photochemical smog and terrestrial toxicity were examined; both, of course, are associated with excess human mortality. Nevertheless, carbon footprints have become the 'currency' of debate in a climate-constrained world [40], where the UK is seeking to dramatically reduce its carbon emissions by 2050. It is therefore of greater significance than these other (important, although perhaps not critical) impact categories. In that regard, shale gas fracking certainly does not "trump renewables".

7. Public and Stakeholder Engagement

UK Government Ministers have indicated their concern over the fierce resistance to their shale gas fracking policies; particularly from rural communities in both the south and north of England (see again Fig. 2). Such communities must be engaged in a two-way dialogue aimed at clarifying the impacts of the shale gas fracking process, along with its potential costs and benefits. Public opposition could prove to be a 'showstopper' for this energy option unless the various stakeholders are engaged in an appropriate consultation. Pigdeon *et al.* [46] recently examined some of the critical issues concerning the design and conduct of public deliberation processes on energy policy matters of national importance. They note that national-level policy issues are often inherently complex; involving multiple interconnected elements and frames, analysis over extended scales, and different (often high) levels of uncertainty. It is their view that facilitators should engage the public in terms of 'whole systems' thinking at the problem scale, provide balanced information and policy framings, and use different approaches that encourage participants to reflect and deliberate on the issues. This is similar to what is often referred to as interactive, participatory methods by the technology assessment community [3-5].

8. Planning, Regulation and Monitoring

One set of issues about which politicians of different persuasions and community groups agree is on the important need for adequate measures in the area of unconventional gas planning and regulation. Nevertheless, it has yet to be determined if what community groups consider effective regulation will be accepted and upheld by the government. For instance, many local groups are opposed to recent moves by the UK Government to facilitate planning permission for fracking by preventing landowners objecting to the process taking place under their land [47]. DECC issues licenses to onshore oil and gas operators for exclusive drilling rights, and have listed a long set of pre-drilling approvals that are needed from the various regulators [1]. Operators are required to obtain planning permission from the appropriate UK minerals planning authority (county council or unitary authorities in England and the planning authorities in Scotland and Wales) and seek access to the site from landowners [1]. It has also been argued that prior evaluations of well integrity should be undertaken before drilling can commence, followed by mandated disclosure of hazardous incidents, ongoing process monitoring and contamination assessments. Public Health England [48], for example, have recently proposed that baseline environmental monitoring be instigated in order to facilitate the impact assessment of shale gas extraction on the environment and public health, that the fracking chemicals (including NORMs) should be publicly disclosed and their risks assessed before use, and that the type and composition of the extracted gas should be determined on a site-by-site basis.

9. Concluding Remarks

An energy technology assessment (ETA) has been undertaken [3-5,13,14] in order to evaluate the credit and debit 'columns' of the shale gas fracking 'balance sheet'. The extraction technology is at a very early stage of development in the UK with great uncertainty over the scale of the potential shale gas resource. An extensive programme of investigative drilling across the country will therefore be needed in order to provide reliable estimates; possibly requiring hundreds of exploratory wells [18,19]. Nevertheless, the successful exploitation of large-scale development of shale gas extraction in the UK might contribute positively in terms of fuel security and independence, as well as jobs and growth, providing the serious problems outlined here can be satisfactorily resolved. But it is unclear whether the latter job creation would be any greater than for equivalent programmes aimed at supporting the adoption of energy demand reduction measures or small-scale low carbon energy options. Similarly, the UK balance of payments would benefit, although it is unlikely that gas bills for household and industrial consumers would fall dramatically as they have done in North America. This is because the UK gas price is determined by the supply and demand across the wider European natural gas market [20].

Hydraulic fracturing requires significant quantities of water which may lead to a fall in the availability of public water supply, ecosystem degradation and adverse effects on aquatic habitats, erosion, and changes in water temperature [26]. Recycled fracking fluid could be used for ongoing fracking operations [26], except that a proportion of this is not recovered. In the USA some concern has been expressed over the possibility of methane levels in water that might be high enough to be flammable [27]. DECC has put in place minimum requirements [27] to avoid groundwater contamination from poorly fabricated wells. The life-cycle carbon footprint of shale gas has been shown to be lower than that of coal-fired power generators providing stringent regulation is implemented to minimise fugitive methane emissions. On the other hand, the life-cycle carbon footprint was shown to be slightly higher than conventional gas, and considerably higher than nuclear power and renewables. It could therefore form part of a transitional UK energy strategy [29], although this might prohibit the attainment of a low (near zero) carbon transition pathway by 2050. The penetrations of shale gas into the UK energy mix would likely lead to the lock-in of gas-fired power generation for some decades. Furthermore, without the large-scale use of carbon capture and storage (CCS) [49] such a transition would be incompatible with meeting legislated carbon budgets and limiting GHG concentrations to a 'safe' level [50].

The socio-economic benefits and costs of shale gas fracking are not evenly distributed between various communities and demographic groups. Thus, the UK overall might benefit from improved energy security and reduced balance of payments, whilst it will be local communities that bear the adverse environmental and health risks of fracking. Induced seismicity caused by the injection of fracking fluid into and along faults that are already under stress can lead to minor earthquakes or surface tremors. However, several prominent UK earth scientists have argued [24,25] that future fracking activities in the UK are only likely to cause 'minor damage'; yet again, provided a robust regulatory framework is put in place. Local environmental impacts are critical to neighbouring communities near the wellhead. They focus on shale fracking site operations at the wellhead, as well as the collection and distribution of unconventional gas from the site [29]. Public resistance has been concerned about increased traffic and vehicle exhaust emissions [48], particularly those emanating from heavy road transport vehicles. In addition, drilling places environmental burdens on landscapes that are often in areas of natural beauty with sensitive wildlife habitats [29].

Acknowledgements

This work is part of a programme of research at the University of Bath on the technology assessment of low carbon energy systems and transition pathways that is supported by a series of UK research grants and contracts awarded by various bodies. In the present context, the first author is jointly leading a large consortium of university partners funded by the UK Engineering and Physical Sciences Research Council (EPSRC) entitled 'Realising Transition Pathways: Whole Systems Analysis for a UK More Electric Low Carbon Energy Future' [under Grant EP/K005316/1]. The authors are grateful for the interaction with other members of the Consortium (and its predecessor) made up of participants from nine UK universities. However, the views expressed here are those of the author alone, and do not necessarily reflect the views of the collaborators or the policies of the funding body.

The authors' names are listed alphabetically.

References

[1] Department of Energy and Climate Change [DECC]. *Onshore oil and gas exploration in the UK: regulation and best practice – England*. London: DECC; 2013.

[2] International Energy Agency [IEA]. *World Energy Outlook: Are we entering a golden age of gas?* Special Report. Paris: IEA; 2011.

[3] Tran TA, Daim T. A taxonomic review of methods and tools applied in technology assessment. *Technological Forecasting and Social Change* 2008; **75**(9): 1396-1405.

[4] Vig NJ, Paschen H, editors. *Parliaments and technology: The development of technology assessment in Europe*. New York: Suny Press; 2000.

[5] Manne AS. ETA: A model of energy technology assessment. *The Bell Journal of Economics* 1976; **7**(2): 379-406.

[6] Chivers D. The big story – Fracking, *New Internationalist* 2013; **468**: 12-24.

[7] Rogers, H. Shale gas – The unfolding story. *Oxford Review of Economic Policy* 2011; **27**(1): 117-143.

[8] Zuckerman G. *The frackers: The outrageous inside story of the new energy revolution*. London: Portfolio Penguin; 2013.

[9] Theodori GL, Luloff AE, Willits FK, Burnett DB. Hydraulic fracturing and the management, disposal, and reuse of frac flowback waters: Views from the public in the Marcellus Shale. *Energy Research & Social Science* 2014; **2**: 66-74.

[10] Broderick J, Anderson K, Wood R, Gilbert P, Sharmina M, Footitt A, Glynn S, Nicholls F. *Shale gas: an updated assessment of environmental and climate change impacts*. [A report commissions by the Co-operative and undertaken by researchers at the Tyndall Centre, University of Manchester] Manchester: Tyndall Centre; 2011.

[11] Lechtenböhmer S, Altmann M, Capito S, Matra Z, Weindrorf W, Zittel W. *Impacts of shale gas and shale oil extraction on the environment and on human health*. [A study by the Wuppertal Institute for Climate, Environment and Energy and Ludwig-Bölkow-Systemtechnik GmbH requested by the European Parliament's Committee on Environment, Public Health and Food Safety. Report IP/A/ENVI/ST/2011-07] Brussels: European Parliament: 2011.

[12] Hammond, GP. Energy, environment and sustainable development: a UK perspective. *Trans. IChemE Part B: Process Safety and Environmental Protection* 2000; **78**(4): 304-323.

[13] Hammond GP, Jones CI, Spevack R. The 'Shoots Barrage': An indicative energy technology assessment of a tidal power scheme. *J. sustain. dev. energy water environ. syst.* 2014; **2**(4): 388-407.

[14] Hammond GP, Hazeldine T. Indicative energy technology assessment of advanced rechargeable battery technologies. *Applied Energy* 2015; **138**: 559-571.

[15] Foxon TJ, Hammond GP, Pearson PJ. Developing transition pathways for a low carbon electricity system in the UK. *Technological Forecasting and Social Change* 2010; **77**(8): 1203-1213.

[16] Hammond GP, Pearson PJG. Challenges of the transition to a low carbon, more electric future: From here to 2050 (Editorial). *Energy Policy* 2013; **52**: 1-9.

[17] Harvey T, Gray J. *The unconventional hydrocarbon resources of Britain's onshore basins – Shale gas*. [Report by the British Geological Survey (BGS)] London: DECC; 2013.

[18] Parliamentary Office of Science and Technology [POST]. *POSTBOX: UK shale gas potential*. London: POST; 2013.

[19] White E, Fell M, Smith L, Keep M. *Shale gas and fracking*. Standard Note SN/SC/6073. London; House of Commons Library; 2014.

[20] Stern JP. *Continental European Long-Term Gas Contracts: is a transition away from oil product-linked pricing inevitable and imminent?* Oxford: Oxford Institute for Energy Studies; 2009.

[21] House of Commons' Energy and Climate Change Committee. *The Impact of Shale Gas on Energy Markets*. HC 785. London: The Stationary Office; 2013.

[22] Department of Energy and Climate Change [DECC]. *Fracking UK shale gas: understanding earthquake risk*. London: DECC; 2014.

[23] Royal Society/Royal Academy of Engineering (RS/RAEng). *Shale gas extraction in the UK: a review of hydraulic fracturing*. DES2597. London: RS/RAEng; 2012.

[24] Davies R, Foulger G, Bindley A, Styles P. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. *Marine and Petroleum Geology* 2013; **45**: 171-185.

[25] Westaway R, Younger PL. Quantification of potential macroseismic effects of the induced seismicity that might result from hydraulic fracturing for shale gas exploitation in the UK. *Quarterly Journal of Engineering Geology and Hydrogeology* 2014; **47**: 333–350.

[26] The Charted Institution of Water and Environmental Management (CIWEM). *Hydraulc fracturing (fracking) of shale in the UK*. Policy Position Statement. London: CIWEM; 2012.

[27] Department of Energy and Climate Change [DECC]. *Fracking UK shale gas: water*. London: DECC; 2014.

[28] Department of Energy and Climate Change [DECC]. *Fracking UK shale gas: safety from design to decommissioning*. London: DECC; 2014.

[29] Helm D. The carbon crunch: How we're getting climate change wrong – and how to fix it. New York and London: Yale University Press; 2012.

[30] Intergovernmental Panel on Climate Change [IPCC]. *Climate Change 2007- The Physical Science Basis. Cambridge:* Cambridge University Press; 2007.

[31] Intergovernmental Panel on Climate Change [IPCC]. *Climate Change 2013 - The Physical Science Basis [Summary for Policymakers]. Cambridge:* Cambridge University Press; 2013.

[32] Jiang M, Griffin WM, Hendrickson C, Jaramillo CP, VanBriesen J, Venkatesh A. Life cycle greenhouse gas emissions of Marcellus shale gas. *Environmental Research Letters* 2011; **6**(3): 034014.

[33] Skone TJ, Littlefield J, Marriott J. *Life cycle greenhouse gas inventory of natural gas extraction, delivery and electricity production*. DOE/NETL-2011/1522. Pittsburgh: US Department of Energy [DOE], National Energy Technology Laboratory [NETL]; 2011.

[34] Hultman N, Rebois D, Scholten M, Ramig C. The greenhouse impact of unconventional gas for electricity generation. *Environmental Research Letters* 2011; 6(4): 044008.

[35] Stephenson, T., Valle JE, Riera-Palou X. Modeling the relative GHG emissions of conventional and shale gas production. *Environmental Science & Technology* 2011; **45**(24): 10757-10764.

[36] Burnham, A, Han J, Clark CE, Wang M, Dunn JB, and Palou-Rivera I. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. *Environmental Science & Technology* 2011; **46**(2): 619-627.

[37] Edwards R, Hass H, Larivé J-F, Lonza L, Maas H, Rickeard D. *Well-to-Wheels analysis of future automotive fuels and powertrains in the European context.* Joint Research Centre (JRC) WELL-TO-TANK Report Version 4a. Luxembourg: Publications Office of the European Union; 2014.

[38] Howarth, R., Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change* 2011; **106**(4): 679-690.

[39] Hischier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, Köllner T, Loerincik Y, Margni M, Nemecek T. *Implementation of Life Cycle Impact Assessment Methods*. ecoinvent Report No. 3 (version 2.2). Dübendorf, Switzerland: Swiss Centre for Life Cycle Inventories; 2010.

[40] Hammond GP, O'Grady A. The threat of an evolving fuel supply to the carbon targets for the UK electricity sector in a more electric dependent future. Proc. 9th Conference on *Sustainable Development of Energy, Water and Environment Systems* [SDEWES], Venice-Istanbul, 20-27 September 2014, Paper SDEWES2014-0365.

[41] MacKay DJ, Stone TJ. *Potential greenhouse gas emissions associated with shale gas extraction and use*. London: DECC; 2013.

[42] Stamford L, Azapagic A. Life cycle environmental impacts of UK shale gas. *Applied Energy* 2014; **134**(0): 506-518.

[43] Heath GA, O'Donoughue P, Arent DJ, Bazilian M. Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation. *Proceedings of the National Academy of Sciences* 2014; **111**(31): E3167-E3176.

[44] Laurenzi IJ, Jersey GR. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. *Environmental Science & Technology* 2013; **47**(9): 4896-4903.

[45] Harvey, T., *Guidance Notes For Onshore Oil And Gas Field Development Plans*. London: DECC; 2014.

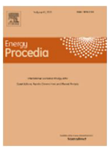
[46] Pidgeon N, Demski C, Butler C, Parkhill K, Spence A. Creating a national citizen engagement process for energy policy. *Proceedings of the National Academy of Sciences* 2014; **111** (Supplement 4): 13606-13613.

[47] Department of Energy and Climate Change [DECC]. *Underground Drilling Access: Government Response to the Consultation on Proposal for Underground Access for the Extraction of Gas, Oil or Geothermal Energy*. London: DECC; 2014.

[48] Public Health England [PHE]. *Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of the Shale Gas Extraction Process*. [PHE-CRCE-009.] London: PHE; 2014.

[49] Hammond GP, Ondo Akwe SS, Williams S. Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage. *Energy* 2011; **36** (2): 975-984.

[50] Committee on Climate Change [CCC]. *The need for a carbon intensity target in the power sector* [Letter from CCC to the UK Secretary of State for Energy and Climate Change, 13 September] London: CCC; 2012.



Biography

Geoffrey Hammond is Professor of Mechanical Engineering at the University of Bath (UK) and was Founder Director of its *Institute for Sustainable Energy and the Environment* (I-SEE). His current research is focused on the technology assessment of energy systems and transitional pathways towards a low carbon future. He has a multi-disciplinary background, including environmental engineering and management. Áine O'Grady is a Research Associate evaluating the energy and environmental performance of low carbon technologies and UK energy transition pathways, whilst David Packham is Emeritus Senior Lecturer in Materials Science with an interest in environmental sustainability. Both are also at the University of Bath.